Phonon mechanisms for excess heat capacity in membrane isolated superconducting transition edge sensors

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Abstract:
The mechanics of phonon transport in membrane-isolated superconducting transition edge sensors is discussed. Surveys of the literature on this type of sensor reveal a number of designs with excess heat capacity and a smaller subset that exhibit decoupling of the superconducting film from the underlying dielectric. A simple model is addressed in which the membrane, despite its thermal isolation, fails to fully thermalize to the temperature of the metal film heating it. A population of phonons exists which is emitted by the metal film, partially thermalizes the dielectric and is then reabsorbed in the metal film without escaping from the device structure to the thermal bath. The size of this population and its contribution to the heat capacity are estimated for several device scenarios.

Phonon mechanisms for excess heat capacity in membrane-isolated superconducting transition edge sensors

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Choice in TES design: watch as phonons futilely attempt to thermalize a dielectric crystal at low temperature

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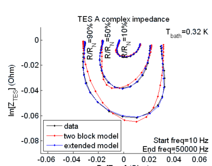
Large membrane silicon bolometers exhibiting excess heat capacity

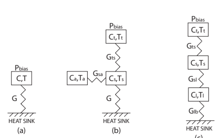
A study undertaken by Zhao examined the role of an internal limit on the thermal conductance in TES bolometer structures exhibiting a large excess heat capacity. Noise and impedance in bolometers with cutouts near the TES were compared with identical structures with no cutouts.

While only small changes in heat capacity (as determined by a fit) were observed, the internal thermal conductance could be varied. Values for this conductance were a factor of 4-10 below the calculated Kapitza resistance value Indicating that the internal conductance between the metal and dielectric was suppressed with and without the additional Cutouts.

(Y. Zhao, J. Appel, J. A. Chervenak, W. B. Doriese, and S. Staggs, IEEE Trans. Appl. Supercond. 21, 227 (2011)

Excess Heat Capacity Discussion – uniform application of a model to determine relative changes in device parameters



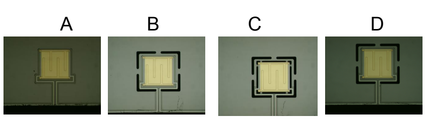


Empirical models for large membrane bolometers have added heat capacities to fit data such as complex impedance. The Zhao study showed that a third heat capacity (in addition to, presumably, the TES metal and Si dielectric) was required to fit the data while two-block models did not fit the data.

The origin of the third heat capacity was unexplained. The suppressed Kapitza conductance between the TES metal and the dielectric could be measured assuming that the excess heat capacity block was after the TES. Models could not distinguish between the dielectric and the base temperature in series or in parallel (as shown in left hand side Fig b and c)

More such models have been explored (for example, I. Maasilta Cond Mat. ArXiv 1205.5693v2 (2012))

Series of Four Test Devices



Part	Pixel Num	Bias power (pW)	Tc (mK)
A (20 μm, no addt'l stencil)	5	39.7	551.7
B (20 μm, 1 stencil)	11	38.2	550.7
C (20 μm, 2 stencil)	9	32.7	550.1
D (5 μm, 1 stencil)	10	9.4	551.3

Tabulated Data from Three Block Models

Param	A	B	C	D	Comment
C_t (pJ/K)	0.25	0.25	0.24	0.22	Similar / higher than expectation
G_{ts}(pW/K)	6130	2810	1200	2250	Engineered by perforations
C_s(pJ/K)	0.89	1.02	1.03	0.96	15% increase in both models
G_a(pW/K)	1220	900	700	470	Hanging model
G_{sl}(pW/K)	1560	1230	990	550	Series model
C_a(pJ/K)	0.65	0.68	0.76	0.56	Hanging model
C_l(pJ/K)	0.90	1.01	1.20	0.68	Series model

Models fit to same impedance curves for T_{base}=320 mK; 50% Rn

Lit survey: Suspected causes of heat capacities

Two level systems (TLS) – surface traps have been suggested and, in roughened SiN films an unexpectedly high heat capacity was observed (Kenyon, 2008). Other measurements (Wang, et. al. 2010) assumed diffusive phonon transport in similar geometries and suggest that amorphous dielectrics (SiN) can have a large "glassy" term (linear in T) added to the Debye heat capacity.

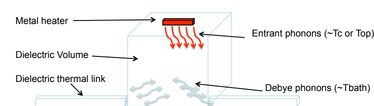
Dielectric surface roughness effects – Since Si crystals have only the T^3 Debye component, surface roughness resulting from fabrication processes could create TLS that affect thermal dissipation in a similarr way. However, roughness without TLS would mainly promote diffusive phonons and improve thermalizationOur samples were produced with care of top and bottom surfaces however the leg edges could have some roughness.

Contamination – Similarly, fabrication processes can attach contaminants to the surface or along the edges of the legs and membrane features. The effects are difficult to disprove though anecdotally the results have been independent of the observable amount of contamination. Further, the effects have been anecdotally observed in devices from a number of different fabrication facilities.

Note: The suppression of the Kapitza conductance from bulk is not aniticipated in these scenarios

Bolometer design (such as leg width) – The SRON group model (LTD, 2011) added a series of heat capacities, assuming a thermal gradient along a straight leg (where transport is more likely to be diffusive). This is similar to the ad hoc modelling of Zhao although with a more narrow focus on where the heat capacity could be located.

A New Suspect: Trapped Population of Excess Ballistic Phonons in the Membrane Volume



Phonons from metal to dielectric just below the metal are well coupled through the passage of phonons through the Kapitza boundary

These phonons are assumed ballistic and (if so, would be) highly unlikely to interact with the dielectric volume not immediately under the metal (Klitsner, Phys Rev B 38, 7576 (1988)) especially in dielectric crystals with polished smooth surfaces as we have presented here.

Since they are trapped in the dielectric volume by the constriction created by the narrow legs yet remain in states well coupled to the small metallized region – some of these phonon excitations can partially thermalize the Si dielectric and be re-absorbed by the metal, creating an excess population of phonons that could effectively add to the total number of phonons contributing to the Debye heat capacity (while simultaneously suppressing the Kapitza conductance).

Debye and Kapitza: Men? Or Myths?

Kapitza coupling of phonons from metal into dielectric has been modified to include dynamics of the atomic motion at the interface to modify the coefficients of transmission and reflection at the interface (Maris, et. al. 1988; Kozorezov, et. al. 1999) In general, heat capacity and thermal conductance are constrained to change together; while our bolometer shows a decoupling of these two such that thermal conductance change and apparent heat capacity change appear to have the opposite sign.

Neither of these formalisms include a term for backscattering from the dielectric bulk back into the metal film. However, suppression from the Kapitza value has been noted in membrane isolated TES (Kilbourne, 1999) and phonon backscattering effects have been invoked in other circumstances to explain the thermo-electrical properties of junctions (K.E.Gray 1969)

Similarly Debye theory is expected to be unmodified for crystalline dielectrics at equilibrium:. The Debye temperature corresponds to a maximum ω_D that is strictly a material property.
Assumes lowest excitation spectrum (Bose Einstein at average temperature) for average occupation numbers of the available phonon states
Assumes typical dispersion relation for energy density of phonon states
Additional terms modifying Debye typically require energy storage capability in the defect or particular mode

Estimates of heat capacity for novel phonon confinement conditions:

Case #1 – emitted phonons are completely non-interacting blackbody of phonons peaked at ω(Tc) filling the dielectric volume

Phonon blackbody (Pbb) is the same formula as the Debye mode calculation for the bulk Si. But instead of absorbing and emitting from the Si walls, it is coupled primarily to the metal film. Given the reduction in the metal film's Kaptiza (~1/10 of expected membrane value), this Pbb could be up to 90% of Cdebye(T=0.55K)

$$C_{tot} \sim C_{debye,\ Si}(T_b) + 0.9 C_{Pbb}(T_c)$$

Even if the silicon membrane temperature approaches the metal film temperature, this estimate remains under a factor of 2 for the possible Cv increase

Case #2 – phonons leaving via the legs are ballistic, those persisting in the membrane increase its energy density through inefficient thermalization

Energy density in the Si membrane is lower than that of the leg (40 pW in the narrow Si legs vs <14 pW to thermalize the membrane)

$$U_{Si} \cong 1941 \int_{Tb}^{Tc} \frac{T^3}{T_D^3} dT \quad \text{Joules/mol}$$

For the 9e-8 moles of Si and a 1 msec time constant of the reported bolometer geometry, the bolometer thermalizes with 14 pW of power transferred through scattered phonons. For a 50 GHz (~0.5 K) mean phonon, this is ~10^{10} phonon absorption events with a similar number removing the hot phonons from the system through the legs. In our example, where the C of the metals is comparable to the C of Si at Tc, the reduction in measured Kapitza conductance and the presence of the phonon confining geometry suggests up to an order of magnitude (~10^{11}) of phonons are present in the membrane. How these additional phonons would fill in the Bose Einstein distribution and affect the calculation of heat capacity is the subject of a future calculation…